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Masterthesis / Review

The use of epidural waveform analysis in the perioperative care and obstetrics: a narrative review

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Abstract

Background: **Epidural anesthesia is widely utilized for postoperative analgesia and intraoperative anesthesia in both surgical and obstetric settings. Despite advancements, conventional techniques still have a significant failure rate, often due to incorrect catheter placement using the LOR method alone. EWA offers a more objective method for confirming epidural space by using a pressure system that detects oscillations synchronized with the pulsatile epidural arterial circulation.**
Study objective: **The objective of this narrative review is to describe the reliability of EWA as well as its added value in different situations.**
Methods: **We included articles sourced from databases MEDLINE, EMBASE, Cochrane Library, and Google Scholar. Screening and eligibility analysis were performed by one reviewer (V.P.). The primary inclusion criterium was the utilization of EWA and its reliability in the operative setting, in pain management as well as in the obstetrical use. We selected 4 prospective trials, 6 observational trials, 1 randomized control trial and 2 systematic reviews.**
Results: **The studies demonstrate the reliability of EWA for epidural needle and catheter placements at cervical to lumbar levels across various surgeries and in laboring patients. Excluding two outliers, sensitivity ranges from 81% to 100%, and specificity from 42% to 100%. One study reported 0% sensitivity due to no pulsatility observed, while another showed 0% specificity due to a single false positive.**
Conclusion: **This review highlights the reliability of EWA for guiding anesthetists during epidural needle and catheter insertion, as well as post-insertion evaluation. EWA is effective across various patient conditions, but further high-quality studies are required to assess its effectiveness in challenging cases, such as patients with higher BMI or anatomical variations, to ensure its broader clinical applicability.**

Keywords: **Epidural anesthesia, epidural waveform analysis, epidural catheter, epidural space.**

Introduction

Epidural anesthesia

Epidural anesthesia is a critical component of pain management in both surgical and obstetric settings, used widely for postoperative analgesia, intraoperative anesthesia, and labor analgesia. This is typically achieved through either direct injection or via an epidural catheter delivering a local anesthetic solution. Despite its widespread use, the technique poses significant challenges, particularly concerning the accurate placement of the epidural catheter[1]. Correct placement of the epidural needle and catheter in the epidural space is essential for effective analgesia, yet failure remains a frequent clinical issue[1]. Misplacement can result in inadequate

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analgesia, necessitating catheter re-siting and increasing the risk of complications such as local anesthetic systemic toxicity (LAST)[2].

A study by Hermanides et al. highlights the need for greater accuracy and reliability in epidural placement[1]. Factors such as the anesthetist's experience play a crucial role in the success rate of epidural blocks, emphasizing the importance of technical proficiency[1]. Conventional methods like the loss-of-resistance (LOR) technique, which involves using a syringe filled with saline or air to identify the epidural space, remain widely used. However, the LOR method is not consistently reliable, particularly in complex cases where a false perception of LOR may occur[3]. The method also relies heavily on the clinician's skill, further contributing to its estimated failure rate of up to 30%[4,1].

Given these challenges, there has been growing interest in alternative techniques and adjunctive devices designed to provide more objective verification of epidural space entry[5]. A range of these alternative techniques are summarized in Table I. Epidural waveform analysis (EWA) represents one of these techniques, which evaluates the pressure waveform generated by oscillations that synchronize with the pulsatile epidural arterial circulation. This pulsatile oscillation is absent when the needle or catheter tip is incorrectly positioned in adjacent anatomical spaces, such as intra-ligamentous or intermuscular planes, physiologic cysts, or peri-ligamentous fat, common sites of epidural failure[6,7].

The aim of this narrative review is to assess the reliability of EWA and examine its potential benefits in different clinical scenarios.

Technique of EWA

EWA involves connecting the epidural catheter or needle to a pressure transducer system. This setup generates a characteristic oscillatory waveform when the catheter tip or needle tip is within the epidural space, reflecting the pulsatile epidural circulation.

As described below (Table II), Klar et al. outlines a practical and efficient approach to implementing EWA using commonly available clinical equipment 2.

Methods

This review included articles sourced from databases MEDLINE, EMBASE, Cochrane Library, and Google Scholar. The search was conducted on September 15th, 2023, and was repeated on February 24th, 2024, to encompass newly published articles. Filters were used to show only articles in English and involving only human patients, without restriction on publication date and level of epidural insertion. The search employed the term "epidural waveform analysis" or "epidural waveform" and titles and abstracts were screened for relevance. Full-text manuscripts of relevant articles were qualitatively assessed. Additionally, reference lists of relevant articles were reviewed for additional pertinent studies. Screening and eligibility analysis were performed by one reviewer (V.P.). The primary inclusion criterium for each study was the utilization of EWA and its reliability.

After full-text reading, we selected 4 prospective trials, 6 observational trials, 1 randomized control trial and 2 systematic reviews. The results of our literature search are given in Figure 1.

Results

EWA versus conventional techniques

In a prospective cohort study conducted by Gong et al., involving over 3,000 patients undergoing thoracic, abdominal, or lower limb surgery, the researchers compared the efficacy of EWA to the LOR technique. They concluded a higher rate of anesthesia satisfaction (62.8% vs 45.6 %; $P<0.05$) and a lower failure rate in the EWA group compared to the LOR group (0.4% vs 1.1%; $P<0.05$)[8]. They characterized failure as the requirement for general anesthesia to complete the surgery.

Chauvin et al. compared the EWA tracings after connecting to the in-situ epidural catheter with the traditional clinical assessments of sensory block to ice. Thoracic epidural catheters were preoperatively placed for postoperative pain control in elective thoracic, gynecologic, vascular, urologic, or general surgery. The initial placement technique preoperatively (i.e., LOR to air or saline, or hanging drop) were at the discretion of the anesthesia provider. The comparison was performed after the administration of epidural local anesthetic to all the patients in the immediate postoperative phase. They found a postoperative EWA sensitivity, specificity, positive predictive value and negative predictive value of 89%, 86%, 98% and 43%, respectively[9].

When EWA is used as an adjunct to the LOR technique, like in the study of Leurcharusmee et al., where 160 patients received a thoracic epidural catheter, they observed a sensitivity of 91% and a specificity of 84%[10]. Arnuntasupakul et al. demonstrated in a multi-center trial that by using EWA as a confirmation tool after thoracic needle placement with LOR compared to LOR alone, a failure rate of 2% was achieved compared with

Table I. — Alternative techniques to confirm the epidural space.

Technique	Elucidation
Membrane in syringe	Combines saline and air in a syringe divided by a plastic membrane, preventing air injection into the epidural space while still providing a compressible feel [24].
Epidural balloon	An inflated balloon attached to the epidural needle hub for visual confirmation of loss of resistance (LOR) as the balloon collapses when the needle enters the epidural space [25]
Epidrum	It comprises a small drum with a diaphragm filled with air, between the epidural needle and syringe, collapsing upon entry into the epidural space [26].
Episure autodetect	It is a LOR syringe equipped with an internal spring that applies continuous pressure on the plunger. Upon entry into the epidural space, the plunger shifts forward, providing objective confirmation of epidural space entry [27].
Acoustic puncture assist device	This device converts pressure changes into an audible signal, altering its beep to alert physicians when the needle penetrates the epidural space as pressure decreases [28].
Epifaith syringe	It incorporates a mechanical device that stops the needle at the point of pressure change upon entering the epidural space, potentially minimizing the risk of accidental dural puncture [29].
Fiberoptic guided	utilizes visible and near-infrared light to differentiate tissues based on their unique optical properties, including reflectance and absorption spectra [30]. Its potential remains unexplored in human studies.
Ultrasound	Preprocedural ultrasound distinguishes tissue types to create a visual image of axial anatomy, facilitating identification of both vertebral space and dura [31].
Optical coherence tomography (OCT)	OCT, similar to ultrasound but optical in nature, offers micron-level imaging resolution, allowing visualization of artery, vein, nerve structures, and the epidural space directly in front of the needle [32].
Epidural stimulation	Electrical stimulation is utilized to assess whether the catheter placement is deemed accurate or inaccurate based on the elicited response [33].
Epidurography	Confirmation of catheter placement can be achieved by injecting a medical contrast medium into the catheter and verifying its position through X-ray imaging [34].

Table II. — Practical approach of implementing EWA by using commonly available clinical equipment.

Equipment needed	Technique
Double-male connector: This is used to bridge connections between components.	**Sterile setup**: A sterile field is crucial, involving the use of sterile gloves and possibly a sterile gown, depending on institutional protocols.
3-way stopcock: Allows for directional control of the flow, facilitating the management of fluid within the system.	**System assembly**: The components are assembled in a sterile environment. The three-way stopcock connects to the saline-filled syringe, the double-male connector, and the arterial pressure extension tubing. The entire system is primed with saline to ensure there are no air bubbles, which can affect the accuracy of the waveform readings.
Arterial pressure extension tubing: Used to extend the connection from the epidural catheter to the pressure transducer.	
Saline-filled syringe: Ensures that the system is primed and free of air, crucial for accurate pressure waveform readings.	**Connection to epidural catheter or needle**: Once primed, the system is connected to the epidural catheter. Care must be taken to maintain sterility during this process, especially when disconnecting and reconnecting parts of the system.
System assembly: The components are assembled in a sterile environment. The three-way stopcock connects to the saline-filled syringe, the double-male connector, and the arterial pressure extension tubing. The entire system is primed with saline to ensure there are no air bubbles, which can affect the accuracy of the waveform readings.	**Saline injection and waveform analysis**: After connecting the system to the epidural catheter or needle, 5 ml of sterile saline is injected to enhance the clarity of the waveform. The waveform is then observed for characteristic pulsatile patterns synchronized with cardiac rhythms, confirming the catheter's placement in the epidural space.

24% failure rate for LOR alone[11]. This study also concluded that the performance time was longer in the EWA group than in the LOR group alone (11.2 ± 6.2 vs 8.0 ± 4.6 minutes; P =0.006), but it can provide more accurate confirmation of catheter placement, as it is less dependent on the operator's skill, especially when it comes to novice operators[11].

In a prospective study, Hong et al. conducted EWA on 105 cervical epidural needle placements following LOR. To validate the success of these placements, fluoroscopy with a contrast medium was performed after recording the epidural waveforms. Fluoroscopy revealed 31 cases where the epidural space was incorrectly identified with LOR, among which 2 exhibited epidural waveforms while 29 did not. The sensitivity, specificity, positive and negative predictive value of EWA was 94.5%, 93.5%, 97.2%, and 87.7%, respectively[12].

In 2006, Lennox et al. conducted a similar prospective study where they performed an EWA on all 81 thoracic epidural needle insertions following LOR. They didn't validate the success of the epidural placement through fluoroscopy, but by testing the catheter with local anesthetic and the presence or absence of an epidural block in the postanesthetic care unit. They reached a sensitivity of 97.5% and a specificity of 100%[3].

Ghia et al. examined the epidural waveforms in all patients who had previously received a thoracic, lumbar, or cervical epidural catheter inserted via LOR. Subsequently, they assessed the catheter's position using computed tomography cathetergram (CTC) and correlated with the presence or absence of waveform prior to the CTC. Both sensitivity and specificity scored 100%[6].

De Medicis et al. evaluated EWA alongside another confirmation technique, namely epidural stimulation test (EST), revealing no discernible differences in reliability between them. EWA demonstrated a sensitivity of 81% and specificity of 17%, while EST exhibited a sensitivity of 80% and specificity of 16%. Combining both techniques resulted in a heightened sensitivity of 97%. Moreover, sensitivity increased with patient age, ranging from 63% in those younger than 40 to 94% in those older than 80 years. However, factors such as the level of epidural insertion, the approach (median versus paramedian), sex, and body mass index did not alter the sensitivity of EWA[13].

Implementation in labor analgesia

Although Sebbag et al.'s study found no pulsatility from the epidural needle and catheter in laboring woman, assuming that the physiological changes in pregnant women may lead to increased tissue compliance and reduced arterial pulsation, several other studies did not encounter this issue[14,15–17]. Al-Aamri et al. elucidated that the lack of pulsative waveforms was due to not flushing the needles with the correct volume of saline before transducing it[17]. In his study, 96% of cases displayed a pulsatile waveform by injecting a saline volume of 5 ml through the epidural needle before connecting the extension tubing[17]. This volume was recommended by an earlier study performed by De Médicis et al., who tested different catheters with different saline boluses to determine the optimal injectate volume for the pulsative waveform transmission[18]. Although previous studies have demonstrated a slightly better waveforms with 5 ml than with 2.5 ml flushed through the catheter, not flushing the catheter at all still showed pressure waveforms in the majority of thoracic epidurals[16,18].

In assessing the reliability of EWA within the delivery suite, two studies were conducted to evaluate its efficacy. In the observational study of Al-Aamri et al., he concluded a sensitivity, specificity, positive and negative predictive value of 95.9%, 66.7%, 98.9% and 33.3%, respectively, when comparing to using a local anesthetic bolus to identify the epidural space[17]. Coccoluto et al. used a Computer Controlled Drug Delivery System with continuous pressure and waveform sensing technology (CCDDS) (CompuFlo® CathCheck™) as a means of confirming the accurate positioning of the catheter within the epidural space in parturients undergoing combined spinal-epidural technique (CSE) for labor analgesia[15]. He measured a sensitivity of 95%, a specificity of 100%, a positive predictive value of 100% and a negative predictive value of 60%[15]. The improved values stem from employing a CCDDS, which enhances the detection of epidural waveforms, particularly crucial in obstetric anesthesia when lumbar epidurals are employed. This significance arises from studies indicating a diminished vertical amplitude height of pulsatile waveforms at lower vertebral column levels, necessitating a more sensitive instrument for optimal detection and hence, a possible explanation of lack of pulsatility in the study of Sebbag et al[19].

High-resolution in-line sensor

To enhance the identification of pulsatile waveforms, certain devices have demonstrated heightened sensitivity in detecting these waveforms, surpassing the capabilities of traditional pressure transducers. The CompuFlo® Instrument represents a computer-controlled drug-delivery system (CCDDS) with high-resolution pressure in-line sensor, designed to accurately gauge tissue pressure in real-time at the needle's orifice[20]. Utilizing an

algorithm, it assesses pressure at the needle tip through a continuous fluid pathway, offering the ability to differentiate various tissue types by continuously furnishing real-time "exit-pressure" data at the needle's tip while in position[20].

Overall results

In recent years, two systematic reviews have been conducted about the reliability and accuracy of EWA.

Hilber et al. included eight studies involving a total of 3901 patients. These studies were evaluated using the QUADAS-2 tool, which is a standardized method for assessing the quality and risk of bias in diagnostic accuracy studies. It evaluates four key domains, patient selection, index test, reference standard, and flow and timing, ensuring that studies are reliable and applicable to clinical practice. The sensitivity of EWA across these studies ranged from 81% to 100%, while specificity ranged from 42% to 100%. Notably, one study did not observe an epidural waveform in parturients, a finding not corroborated by another study, highlighting some inconsistencies in the data [21]. The study suggests that EWA has the potential to enhance the accuracy of epidural space identification, which could lead to improved clinical outcomes in surgical and labor analgesia. However, more standardized research and broader clinical validation are needed to fully integrate EWA into routine clinical practice.

In 2023, Pinho et al. reviewed the use of EWA in confirming the identification of the epidural space in adults with acute pain[22]. Following assessment with the QUADAS-2 tool, 22 studies were included, with 9 utilized for meta-analysis. An overall sensitivity of 90% and specificity of 88% were determined. Pinho et al. concluded that pressure waveform analysis appears clinically beneficial, albeit requiring cautious interpretation due to challenges in distinguishing between intravascular and intrathecal catheters. Future clinical trials focusing on patients with complex anatomy are anticipated to provide valuable insights.

To conclude, we summarized the sensitivity and specificity of the individual studies in Table III. Note that Hilber et al. didn't provide an overall score of the sensitivity and specificity of their included studies[21]. The specificity in the study of Sebbag et al. cannot be calculated as no epidural waveforms were recorded[14].

Discussion

Due to the existing variability in the success rates of epidural anesthesia, which can be attributed to the subjective nature of the LOR method and the potential for anatomical variations, there is a clear need for more reliable techniques to confirm epidural catheter placement. EWA is a straightforward method through which anesthetists can verify the position of the needle and/or catheter tip within the epidural space by utilizing a pressure measurement system[3,6]. It is important to note that inadvertent intravascular placement of the needle or catheter tip results in waveform characteristics that differ distinctly from those observed within the epidural space[9].

The evidence suggests that EWA demonstrates considerable sensitivity, highlighting its reliability when pulsations are detected. However, caution must be exercised, as pulsations may also occur in intrathecal or intravascular catheter positions.

Table III. — The sensitivity and specificity of the individual studies. CI: confidence interval; CBC: cannot be calculated due to a denominator of zero.

Study	Sensitivity (95% CI)	Specificity (95% CI)
1. Gong et al. 2014 [8]	100% (100 - 100)	42% (32 - 52)
2. Chauvin et al. 2022 [9]	89% (80 - 94)	86% (49 – 98)
3. Leurcharusmee et al. 2015 [10]	91% (85 – 95)	84% (69 – 92)
4. Arnuntasupakul et al. 2016 [11]	98% (89 – 100)	00% (00 – 97)
5. Hong et al. 2018 [12]	95% (90 – 98)	94% (84 – 99)
6. Sebbag et al. 2016 [14]	00% (00 – 28)	CBC
7. Al-Aamri et al. 2017 [17]	96% (90 – 98)	100% (34 – 100)
8. Coccoluto et al. 2021 [15]	94% (81 – 98)	100% (44 – 100)
9. Lennox et al. 2006 [3]	98% (92 – 100)	100% (34 – 100)
10. Ghia et al. 2001 [6]	100% (57 – 100)	100% (65 – 100)
11. De Medicis et al. 2005 [13]	81% (75 – 86)	100% (63 – 100)
12. Hilber et al. 2019 [21]	From 81% to 100% No overall score of sensitivity	From 42% to 100% No overall score of specificity
13. Pinho et al. 2023 [22]	90% (72 – 97) Overall score of sensitivity	88% (78 – 94) Overall score of specificity

Aspiration through the catheter can help differentiate between these positions. Furthermore, given the substantial variability in specificity reported across studies, the absence of pulsations does not necessarily indicate incorrect catheter or needle placement. In such cases, clinical examination can provide valuable corroboration.

Despite differences in study methodologies, such as whether EWA is applied through the epidural needle or catheter, a randomized comparison study by Tangjitbampenbun et al. found that these two approaches had comparable performance times and efficacy, as measured by success rates and postoperative analgesia[23]. This suggests similar levels of accuracy between the needle and catheter approaches in the application of EWA[23].

EWA proves especially useful in various clinical scenarios, particularly when traditional methods, such as ice testing for catheter functionality, are impractical. First, in CSE procedures for pregnant women, where spinal anesthesia is concurrently administered, EWA provides a reliable alternative for assessing epidural catheter functionality, even when spinal anesthesia remains effective. Second, epidural catheters are often placed in operating theatres well before surgery commences, allowing time to utilize EWA, despite its slightly more time-consuming nature. These catheters are typically used after surgery has begun, when the patient is under general anesthesia, rendering traditional tests with local anesthetics or ice unfeasible. In instances of intraoperative pain under general anesthesia, EWA serves as a crucial tool for reassessing catheter placement without the risks associated with additional local anesthetic boluses, thus facilitating prompt adjustments to postoperative analgesia, and ensuring optimal pain management.

Furthermore, in pediatric cases, where epidural catheters are placed while the child is under general anesthesia, EWA can significantly enhance both the safety and accuracy of catheter placement. Postoperatively, if a patient experiences pain in the recovery unit, EWA offers a safer alternative for assessing catheter position compared to administering additional local anesthetic, which could pose risks if the catheter is misplaced.

The interpretation of EWA, however, may vary between operators and can sometimes present challenges. The use of high-resolution, in-line pressure sensors, such as the CCDDS, can enhance the accuracy of catheter evaluation by providing clearer and more interpretable results. Additionally, the CCDDS offers educational benefits by providing visual and auditory feedback, helping trainees to recognize the tactile sensation of passing through the ligamentum flavum and entering the epidural space.

Nonetheless, EWA is not without its limitations. In urgent situations, such as the rapid preparation for an emergency caesarean section, the time required to perform EWA may be prohibitive. Moreover, the absence of pulsations during EWA does not definitively indicate incorrect catheter placement, as demonstrated by the low specificity in some studies. This could lead to unnecessary adjustments or repositioning of correctly placed catheters.

While EWA shows significant promise, current research primarily consists of prospective and observational studies. Further high-quality studies, particularly randomized controlled trials, are necessary to validate its efficacy. Additionally, as waveform interpretation is operator-dependent, comprehensive training programmes are crucial to ensuring practitioners' proficiency with this novel technology. Such initiatives will be instrumental in maximizing the potential benefits of EWA and advancing the field of epidural anesthesia.

Conclusion

In conclusion, the variability in success rates of epidural anesthesia, largely due to the subjective nature of the LOR method and anatomical differences, underscores the need for more reliable techniques for confirming epidural catheter placement. EWA emerges as a promising tool that offers a straightforward method for verifying needle and catheter tip positions within the epidural space. While EWA demonstrates considerable sensitivity, particularly in detecting pulsations, caution is necessary due to the potential for similar pulsations in intrathecal or intravascular catheter placements. The technique is especially valuable in clinical scenarios where traditional methods, such as ice testing, are impractical, including CSE procedures in pregnant women, pediatric cases, and intraoperative pain management under general anesthesia. Although EWA shows promise, its interpretation can be operator-dependent, and the technique is not without limitations, particularly in emergency situations or cases of absent pulsations.

Further research, particularly high-quality randomized controlled trials, is essential to validate EWA's efficacy. Moreover, the development of comprehensive training programmes for practitioners is crucial to ensuring the consistent and proficient use of this technology. With appropriate validation and training, EWA has the potential to significantly advance the practice of epidural anesthesia, improving safety and outcomes in a range of clinical settings.

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